



Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

# Longitudinal and Transverse Spin Transfers of $\Lambda$ and $\bar{\Lambda}$ Hyperons in Polarized $p$+$p$ Collisions at $\sqrt{s} = 200$ GeV at RHIC-STAR

**Yike Xu (许一可)**

**(for the STAR Collaboration)**

**Shandong University**


XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects

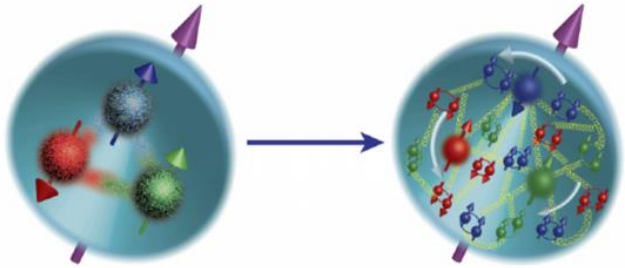
# Outline

- Motivation
- RHIC & STAR Detector
- $\Lambda$ and $\bar{\Lambda}$ Hyperons Selections
- Longitudinal Spin Transfer Measurements
- Transverse Spin Transfer Measurements
- Summary

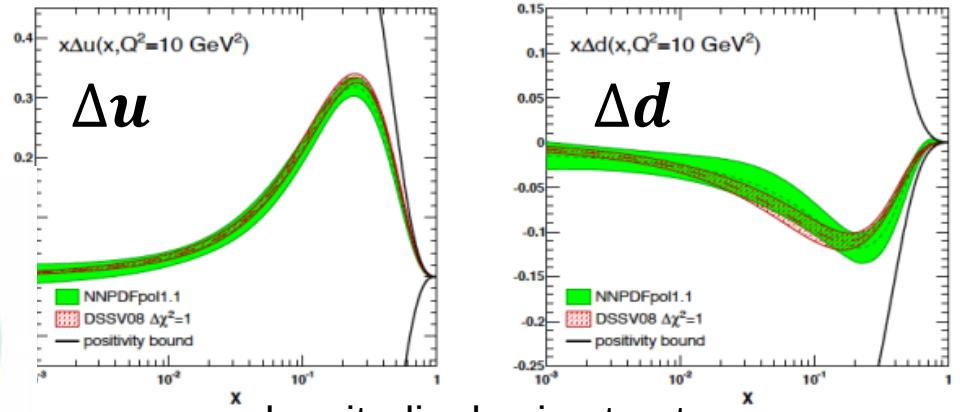
# Motivation

- Nucleon spin structure sum rule

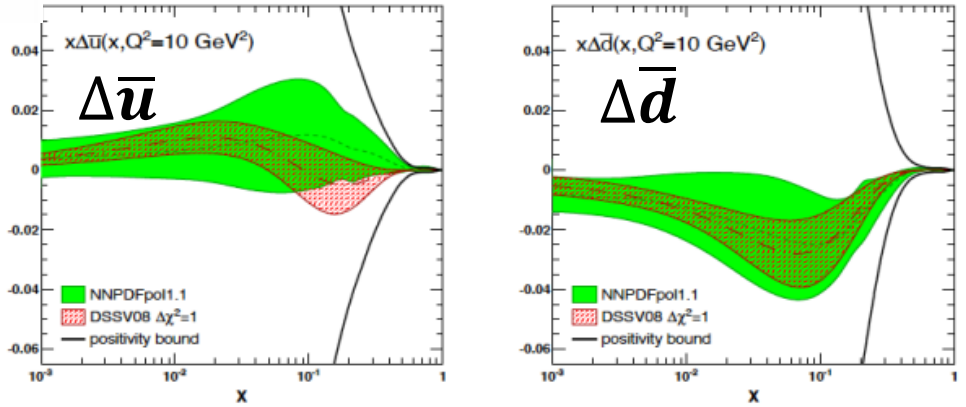
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,\bar{q},g}$$



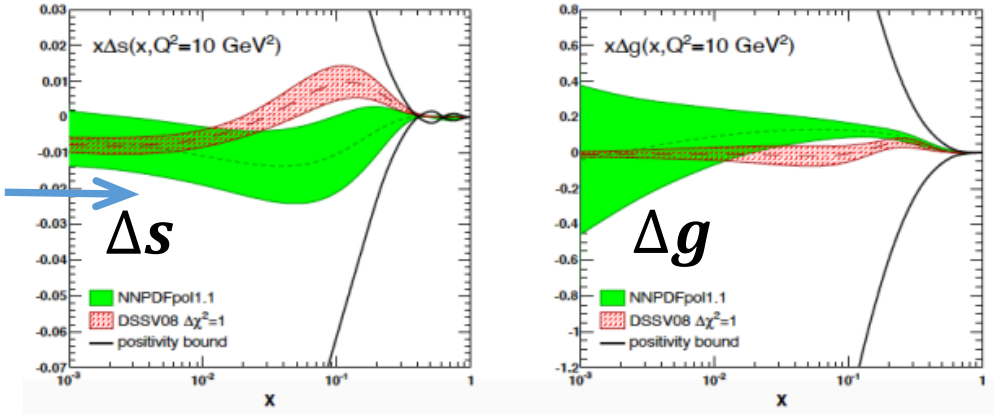
| | |
|---|---|
| **Valence quark** | well known |
| **Sea quark** | still have large uncertainty |




longitudinal spin structure




NNPDFpol1.1, Nucl. Phys. B887,276 (2014)




- Knowledge about the proton spin structure has been obtained from DIS and pp experiments.

- The sea quark contribution to the proton spin, for example, the polarized distributions of the **strange quark(anti-quark), $s(\bar{s})$, is still not well constrained** by experimental data.

# Why Λ ?

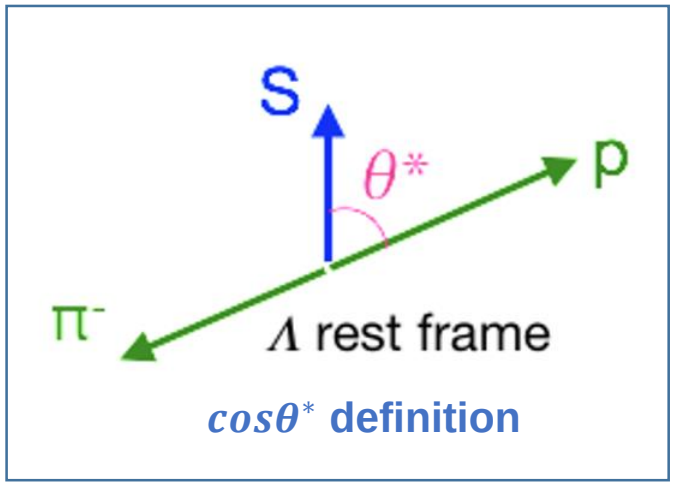
- **Λ contains a strange constitute quark, which is expected to carry most of Λ spin:**

$$|\Lambda^{\uparrow}\rangle = (ud)_{00}s^{\uparrow}$$

- **The Λ polarization,** $P_{\Lambda(\bar{\Lambda})}$, can be extracted from the angular distribution of the weak decay channel ($\Lambda \rightarrow p\pi^-$):

$$dN \propto \left(1 + \alpha P_{\Lambda(\bar{\Lambda})} cos\theta^*\right) d cos\theta^*$$

$\alpha$ is the decay parameter, $\alpha$= 0.732±0.014



$cos\theta^*$ **definition**

- **Λ decay channel:**

$\Lambda \rightarrow p\pi^-$ $(branch\ ratio \sim 64\%)$
$\Lambda \rightarrow n\pi^0$ $(branch\ ratio \sim 36\%)$

# Longitudinal spin transfer $D_{LL}$ in p+p collisions

- **Longitudinal spin transfer $D_{LL}$ in p+p collisions** can provide connections to the helicity distribution of the $s(\bar{s})$ in the proton and polarized fragmentation function (FF).

$$D_{LL}^{\Lambda} \equiv \frac{\sigma^{(p^+p\to\Lambda^+X)} - \sigma^{(p^+p\to\Lambda^-X)}}{\sigma^{(p^+p\to\Lambda^+X)} + \sigma^{(p^+p\to\Lambda^-X)}} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\Delta\sigma^{\Lambda} = \sum_{abcd} \int dx_a\, dx_b dz \Delta f_a(x_a) f_b(x_b) \Delta\sigma^{(a^{\to}b\to c^{\to}d)} \Delta D_c^{\Lambda}(z)$$

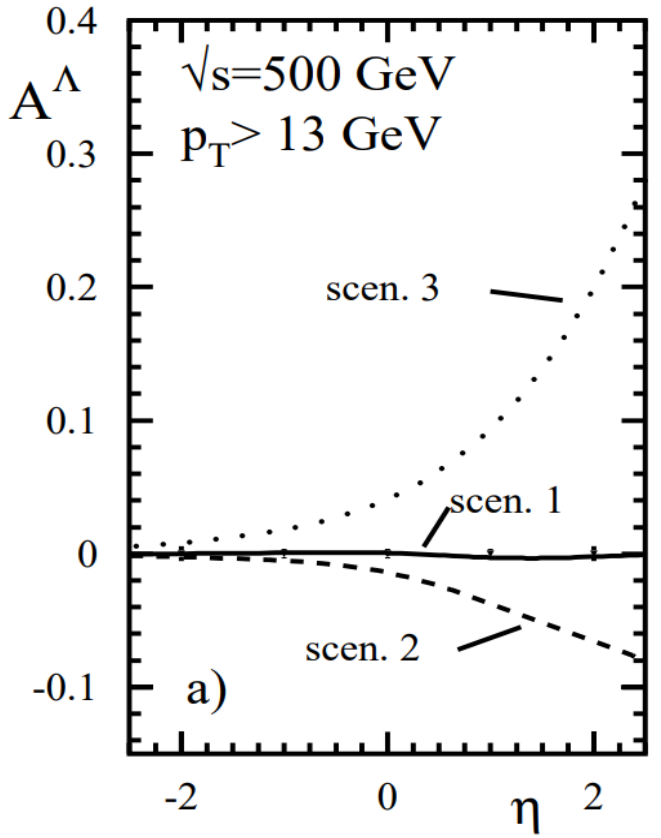
Polarized FF

pQCD

- **Helicity distributions:** $\Delta f_a(x_a) = f_a^+(x_a) - f_a^-(x_a)$

➢ $D_{LL}$ predictions in pp with modeling of polarized FF:

C. Boros, J.T.Londergan, A.W.Thomas, Phys. Rev. D62, 014021 (2000)
B.Q. Ma, I.Schmidt, J.Soffer, J.J.Yang, Nucl. Phys. A703, 346 (2002)
Q. Xu, C.X. Liu, Z.T. Liang, Phys. Rev. D65, 114008 (2002)




Predictions for the Λ polarization at the RHIC

D.de Florian, M.Stratmann, and W.Vogelsang, PRL81 (1998)530

# Transverse spin transfer $D_{TT}$ in p+p collisions

- **Transverse Spin transfer $D_{TT}$ in p+p collisions** can provide connection to the transversity distributions of the $s(\bar{s})$ in the proton

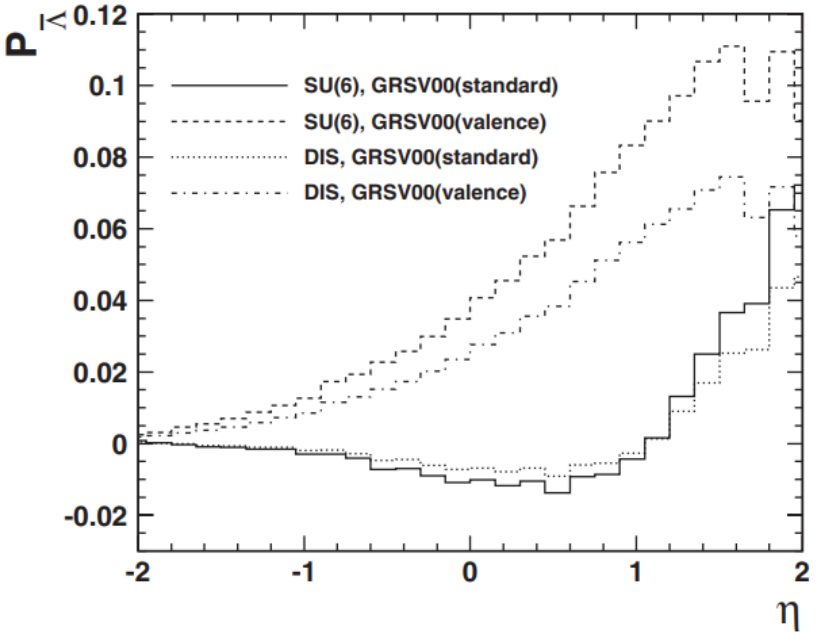
$$D_{TT}^{\Lambda} \equiv \frac{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} - \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}}{\sigma^{(p^{\uparrow}p\to\Lambda^{\uparrow}X)} + \sigma^{(p^{\uparrow}p\to\Lambda^{\downarrow}X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\delta\sigma^{\Lambda} = \sum_{abcd} \int dx_a\, dx_b dz \delta f_a(x_a) f_b(x_b) \delta\sigma^{(a^{\uparrow}b\to c^{\uparrow}d)} \delta D_c^{\Lambda}(z)$$

$\delta\sigma^{(a^{\uparrow}b\to c^{\uparrow}d)}$: pQCD

$\delta D_c^{\Lambda}(z)$: Polarized FF

- **Transversity distributions:** $\delta f_a(x_a) = f_a^{\uparrow}(x_a) - f_a^{\downarrow}(x_a)$
  -it is much less known due to its chiral-odd nature.

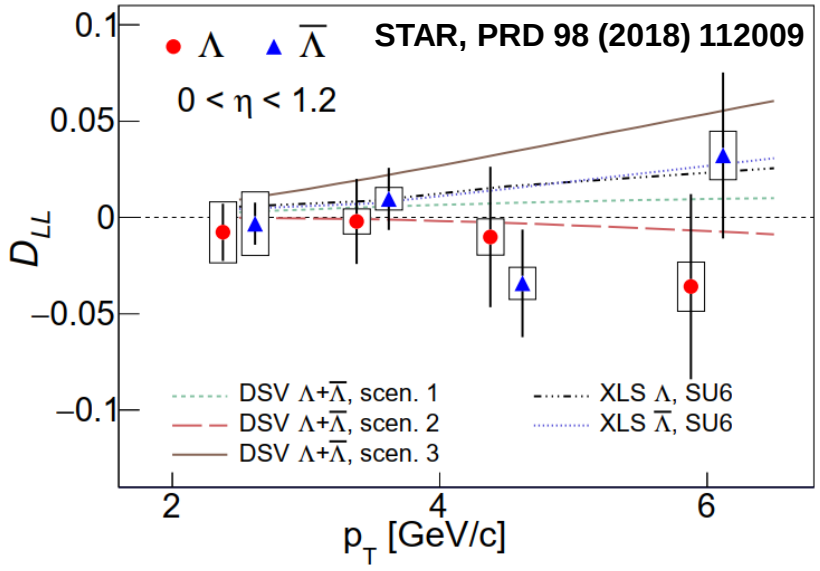


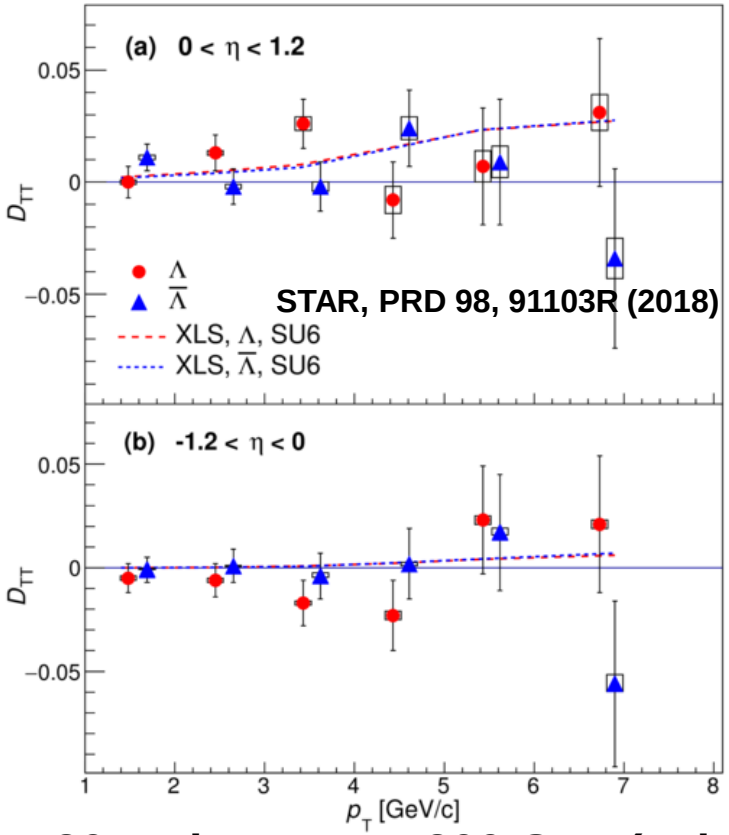

Q. Xu, Z. T. Liang, E. Sichtermann, PRD73, 077503 (2006).

# Recent measurements of $D_{TT}$ and $D_{LL}$ at STAR

- **Longitudinal and transverse spin transfers** have been measured at STAR using 2009 and 2012 data, respectively.

- Previous measurements of $D_{TT}$ and $D_{LL}$ are consistent with the model predictions, and also consistent with zero.




- **Measurement precision** needs to be further improved.

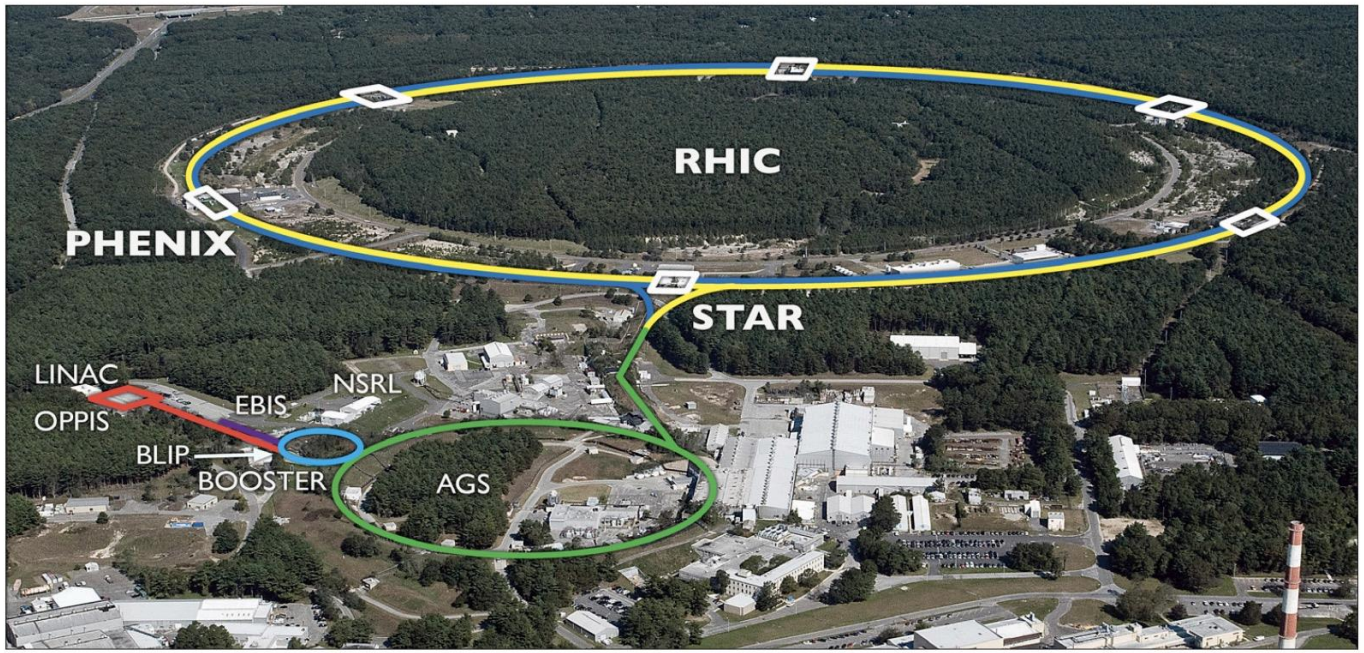
- **$D_{LL}$ and $D_{TT}$ have now been measured at STAR using the 2015 data set at 200 GeV (twice as large as the previous data sets).**

# Relativistic Heavy Ion Collider

- **RHIC is the world's first (and only) polarized hadron collider.**

  RHIC consists of two 3.8 km circumference long quasi-circular concentric rings, one ("Blue") clockwise and the other ("Yellow") for counter-clockwise beams movement.

- **The rings can be filled with polarized beams with all 4 combinations of spin states ++, --, +-, -+.**




+ + - - + + - -

**Yellow beam**

+ - + - + - + -

**Blue beam**

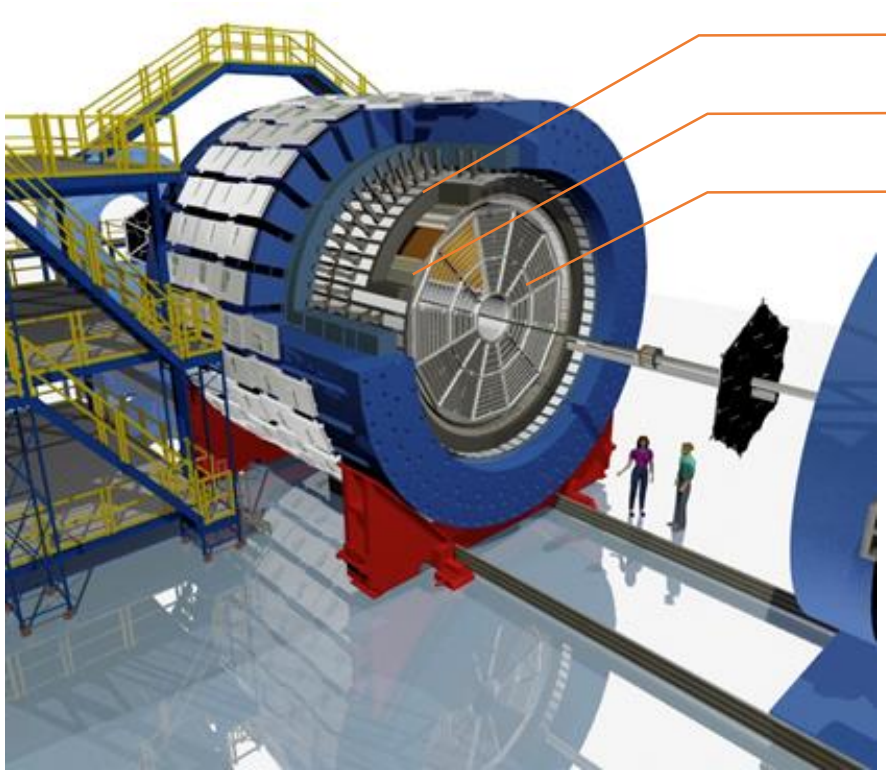
- For p+p, RHIC can run at $\sqrt{s} = \mathbf{200\ GeV}$ and $\sqrt{s} = \mathbf{510\ GeV}$ with beams longitudinally or transversely polarized.

- **In 2015**, we have **283 M** good events in **transversely polarized** collisions, and **215 M** good events in **longitudinally polarized** collisions at **200 GeV.**

- 2015 beam transverse polarization:
  - Blue beam: ~57%
  - Yellow beam: ~57%
- 2015 beam longitudinal polarization:
  - Blue beam: ~52%
  - Yellow beam: ~56%

# Solenoidal Tracker At RHIC

**For $D_{TT}$ and $D_{LL}$ analysis, the following sub-detectors were used:**




- **TPC is our main detector to measure the track's momentum and PID information.**
  - covering $|\eta| < 1.3$ and $\varphi \in [0,2\pi]$.

- **TOF is used to improve PID for hyperon daughter tracks.**

- **EMC includes BEMC (Barrel EMC) and EEMC (Endcap EMC)**
  - BEMC: covering $|\eta| < 1.0$ and $\varphi \in [0,2\pi]$.
  - EEMC: west only, covering $1.086 < \eta < 2.00$ and $\varphi \in [0,2\pi]$.

- BBC (Beam-Beam Counter) and VPD (Vertex Position Detector) can be used to monitor the luminosity.

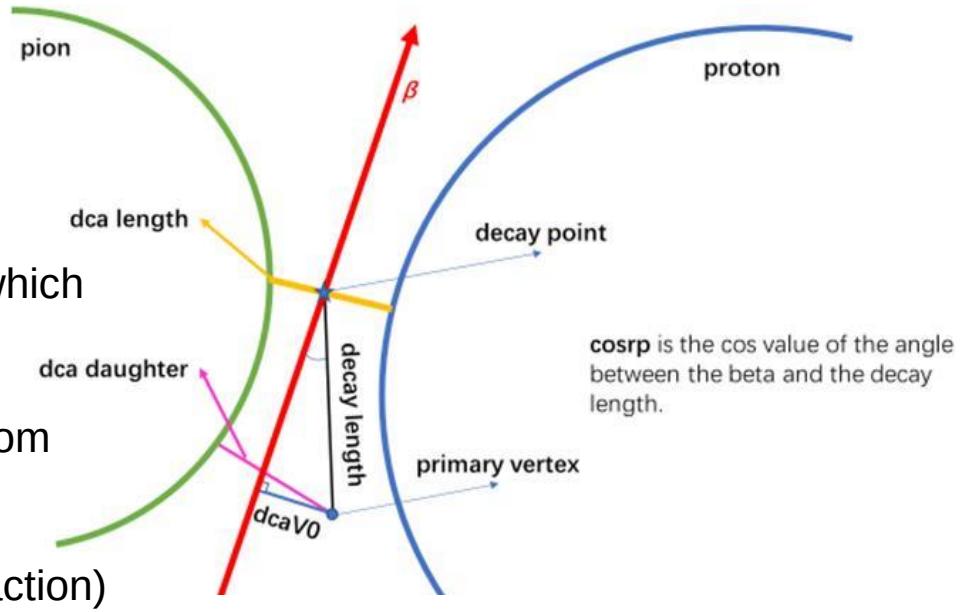
- We select the **hard scattering events** by Jet Patch trigger which is based on energy depositions in the **EMC**.

# $\Lambda$ and $\bar{\Lambda}$ reconstruction

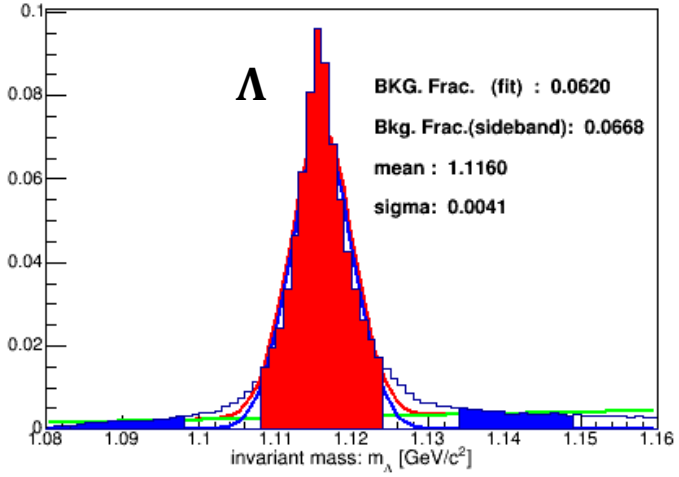
- Proton and pion tracks are **paired** to reconstruct the $\Lambda$ and $\bar{\Lambda}$ candidates.
- A series of **topological cuts** are tuned to further reduce the background.
- **Side-band method** is used to estimate the residual background fraction, which is **less than 10%.**
- The spin transfer of the signal is obtained by subtracting the contribution from residual background with:

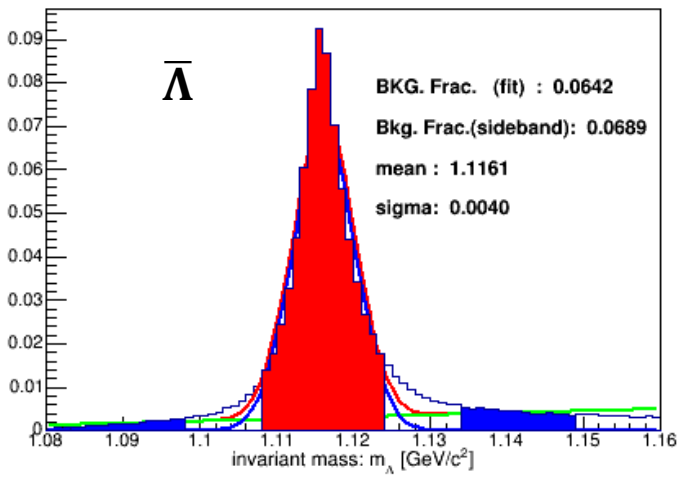
$$D_{TT} = \frac{D_{TT}^{raw} - rD_{TT}^{bkg}}{1 - r}$$ ($r$ is the background fraction)

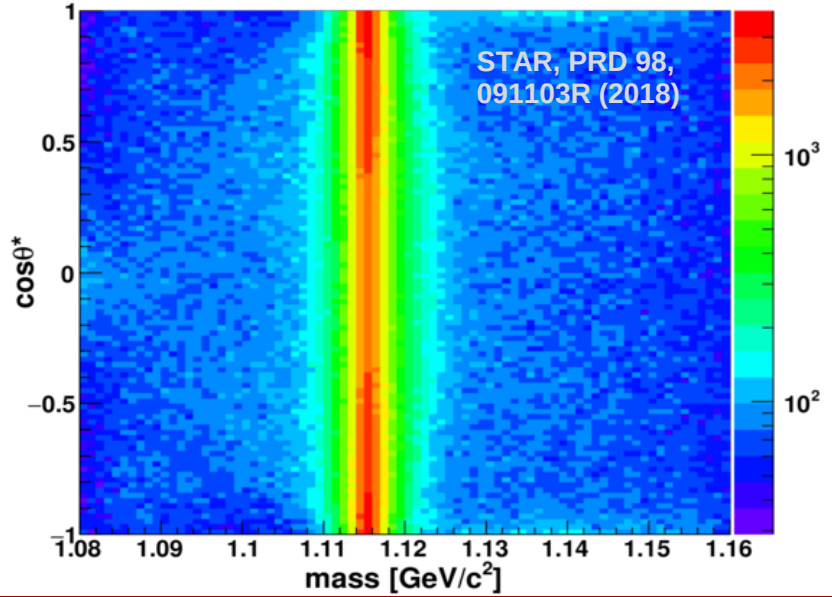
Topological cut




**Examples of invariant mass distribution for $D_{TT}$ of $\Lambda$ and $\bar{\Lambda}$ in $p_T$ 3~4 GeV**



# $D_{LL}$ measurements

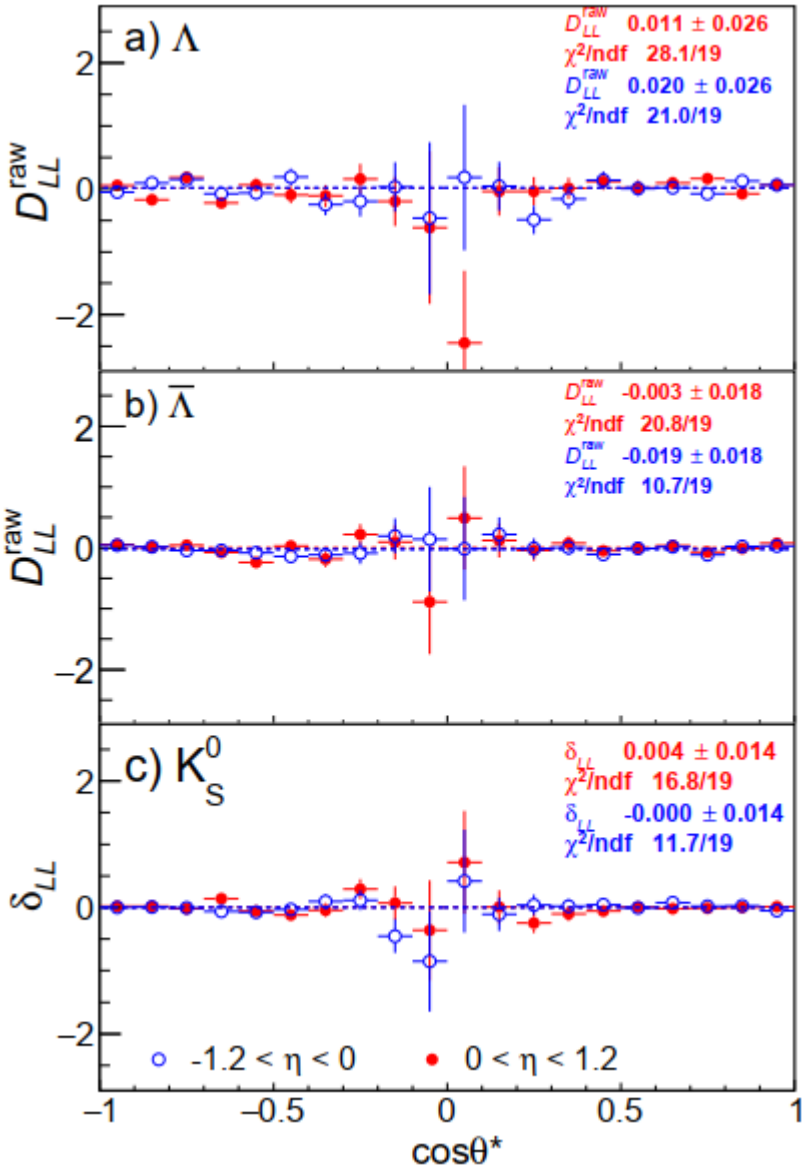
- **$D_{LL}$ is extracted by:**

$$D_{LL} = \frac{1}{\alpha P_{beam} \langle cos\theta^* \rangle} \frac{N^+ - RN^-}{N^+ + RN^-}$$

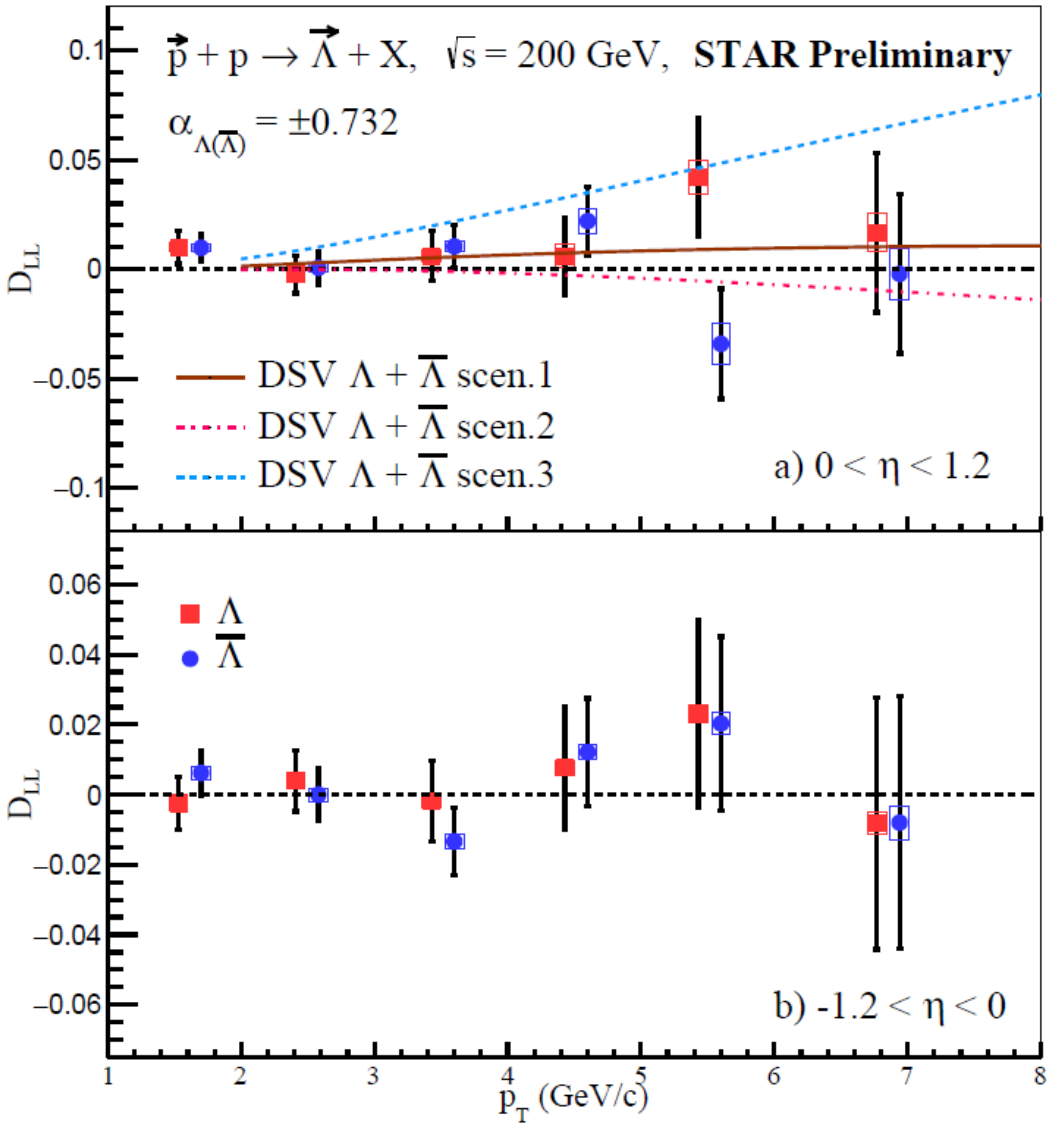
  - ✓ $\langle cos\theta^* \rangle$ is the average value of each $cos\theta^*$ bin
  - ✓ $N^{+/-}$ is the $\Lambda$ counts in a $cos\theta^*$ bin when the helicity of the polarized beam is positive/negative
  - ✓ $R$ is the relative luminosity recorded by VPD: $R = \mathcal{L}^+/\mathcal{L}^-$
  - ✓ $\alpha = 0.732 + 0.014$, is the decay parameter
  - ✓ $P_{beam}$ is the beam polarization.

- $K_S^0$ was also reconstructed as a null check of our method. The extracted "spin asymmetry“ ($\alpha$ of $K_S^0$ is assumed equal to 1) is consistent with 0.

STAR, PRD 98 (2018) 112009



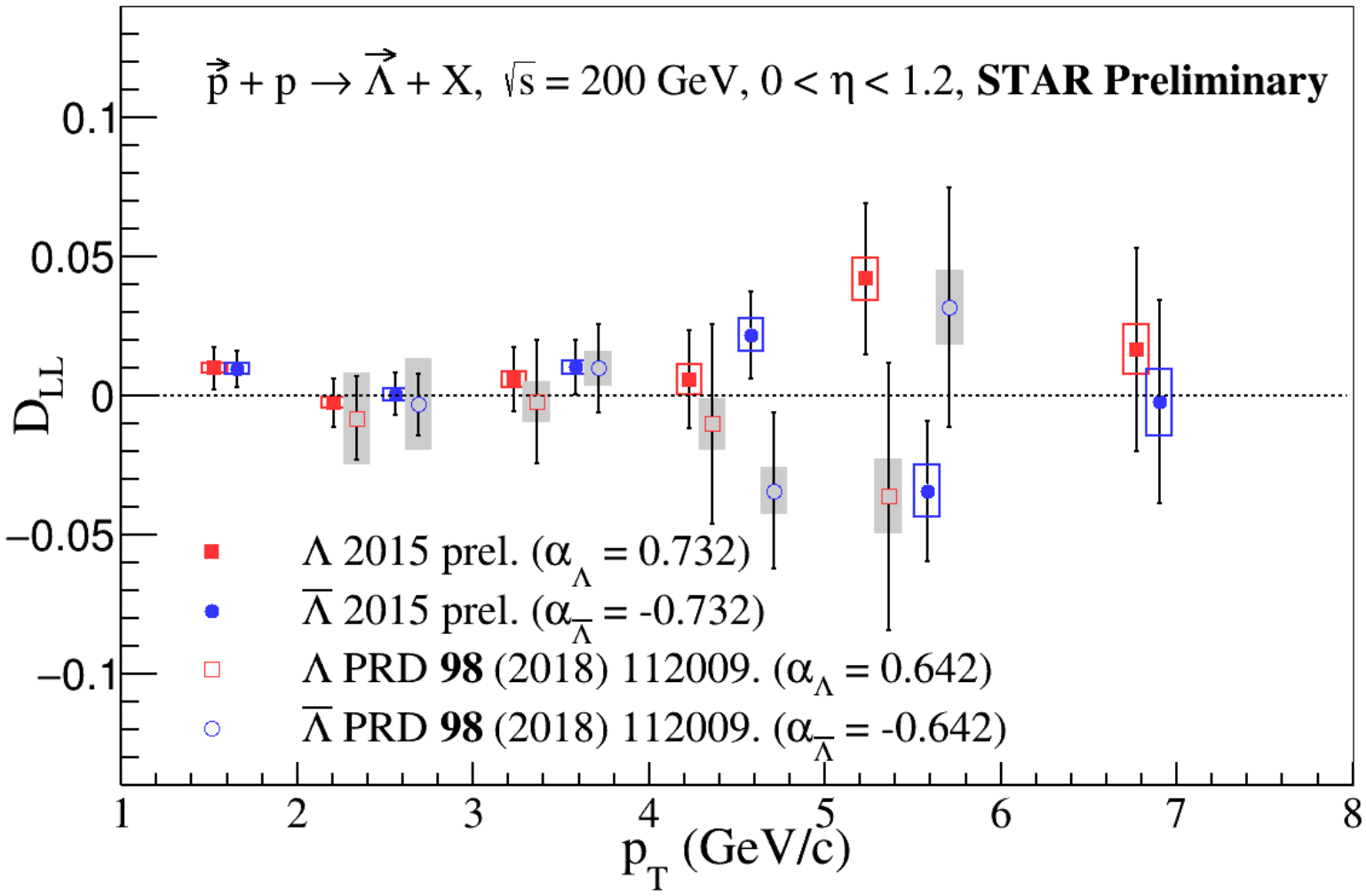
# New $D_{LL}$ results from STAR 2015 data




- New $D_{LL}$ results versus $p_T$ for $\Lambda$ and $\bar{\Lambda}$ in pp collisions at 200 GeV.
- The results are consistent with zero within uncertainties.
- Results could not distinguish among different model scenarios (D.de Florian, M.Stratmann, and W.Vogelsang, PRL 81 (1998) 530).

Note: The $\Lambda$ results have been offset to slightly smaller $p_T$ values for clarity.

# $D_{LL}$ results comparison from STAR 2015 data and 2009 data




Note: The previously published results have been offset to slightly larger $p_T$ values.

- The new $D_{LL}$ results are consistent with previous 2009 data.
- The new $D_{LL}$ extended to $p_T$ ~7 GeV .
- A factor of $\sim\sqrt{2}$ improvement in statistical precision.

# $D_{TT}$ measurements

## -The lambda polarization direction for $D_{TT}$

- The direction of transverse polarization is **rotated along the normal** direction of the scattering plane in partonic scattering.

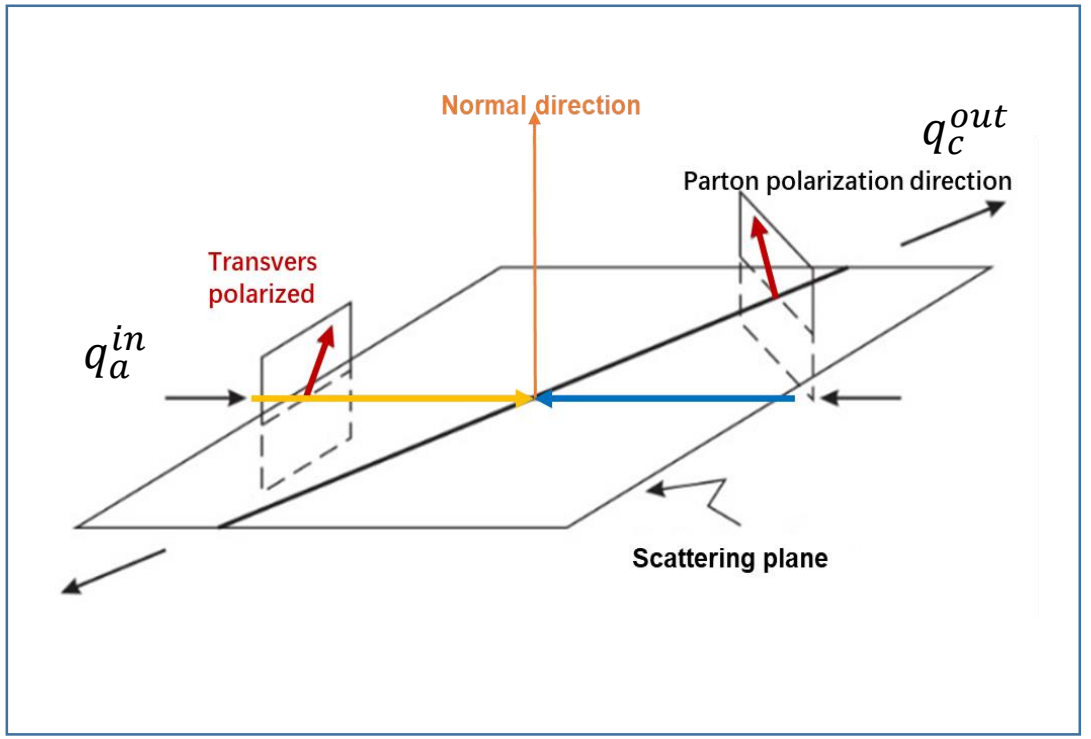
- $D_{TT}$ is measuring the spin transfer to the final state polarization along the pol. direction of outgoing hard quark.
- Jet axis associated with the hyperon is used to obtain the polarization direction after rotation.

- **The anti-$k_T$ algorithm with $R = 0.6$ to reconstruct jets**.

- Require $\eta_{jet}$ ~ (-0.7, 0.9), $p_T$ > 5.0 GeV/c

- $\Delta R$ used to correlate $\Lambda(\bar{\Lambda})$ candidate with a jet (Require $\Delta R < 0.6$).

$$\Delta R = \sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$$
$$\Delta\phi = \phi_\Lambda - \phi_{jet}$$
$$\Delta\eta = \eta_\Lambda - \eta_{jet}$$




J.Collins, S.Heppelmann, G.Ladinsky, NPB420 (1994)565

# Cross-ratio method for $D_{TT}$

- $D_{TT}$ is extracted from a **cross-ratio asymmetry** using $\Lambda$ counts with opposite beam polarization within a small interval of $cos\theta^*$

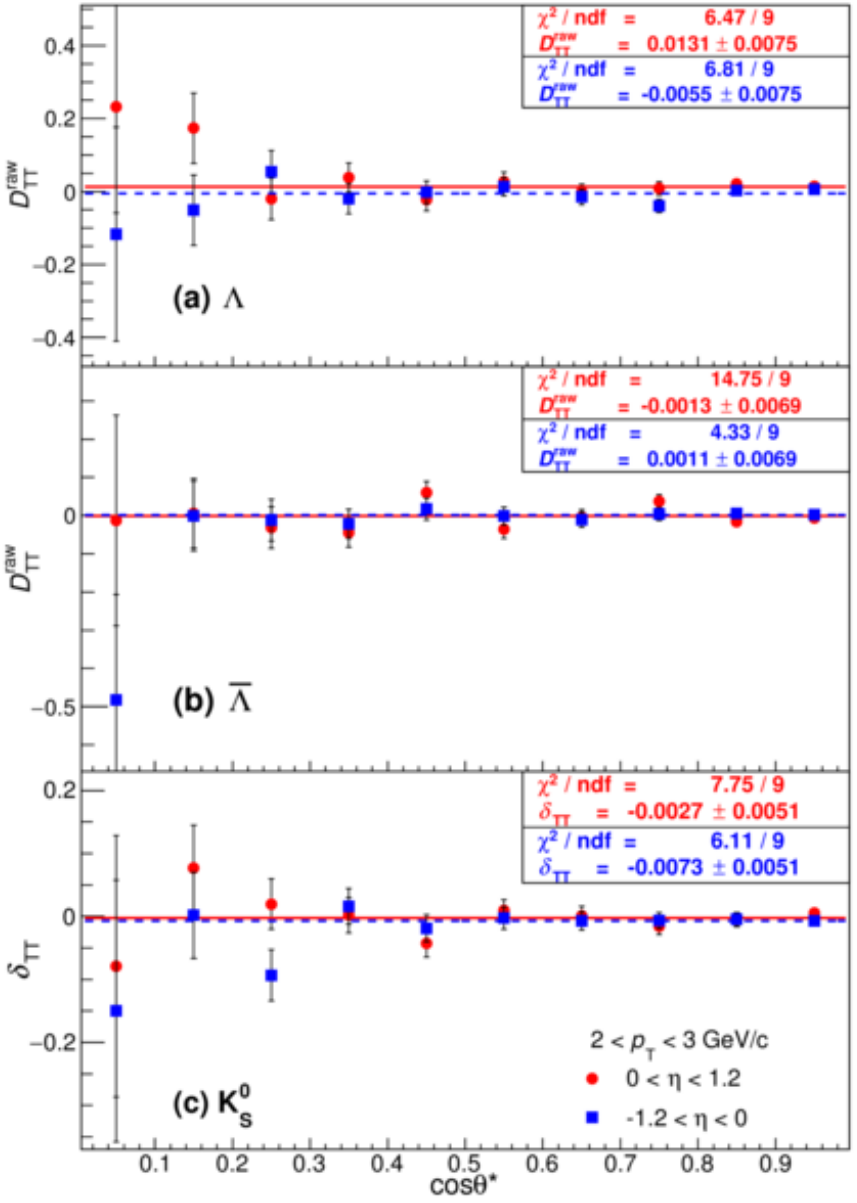
$$D_{TT} = \frac{1}{\alpha P_{beam}\langle cos\theta^* \rangle} \frac{\sqrt{N^{\uparrow}(cos\theta^*)N^{\downarrow}(-cos\theta^*)} - \sqrt{N^{\uparrow}(-cos\theta^*)N^{\downarrow}(cos\theta^*)}}{\sqrt{N^{\uparrow}(cos\theta^*)N^{\downarrow}(-cos\theta^*)} + \sqrt{N^{\uparrow}(-cos\theta^*)N^{\downarrow}(cos\theta^*)}}$$

✓ **Here the relative luminosity and the acceptance are both canceled, which helps to reduce systematic uncertainty.**

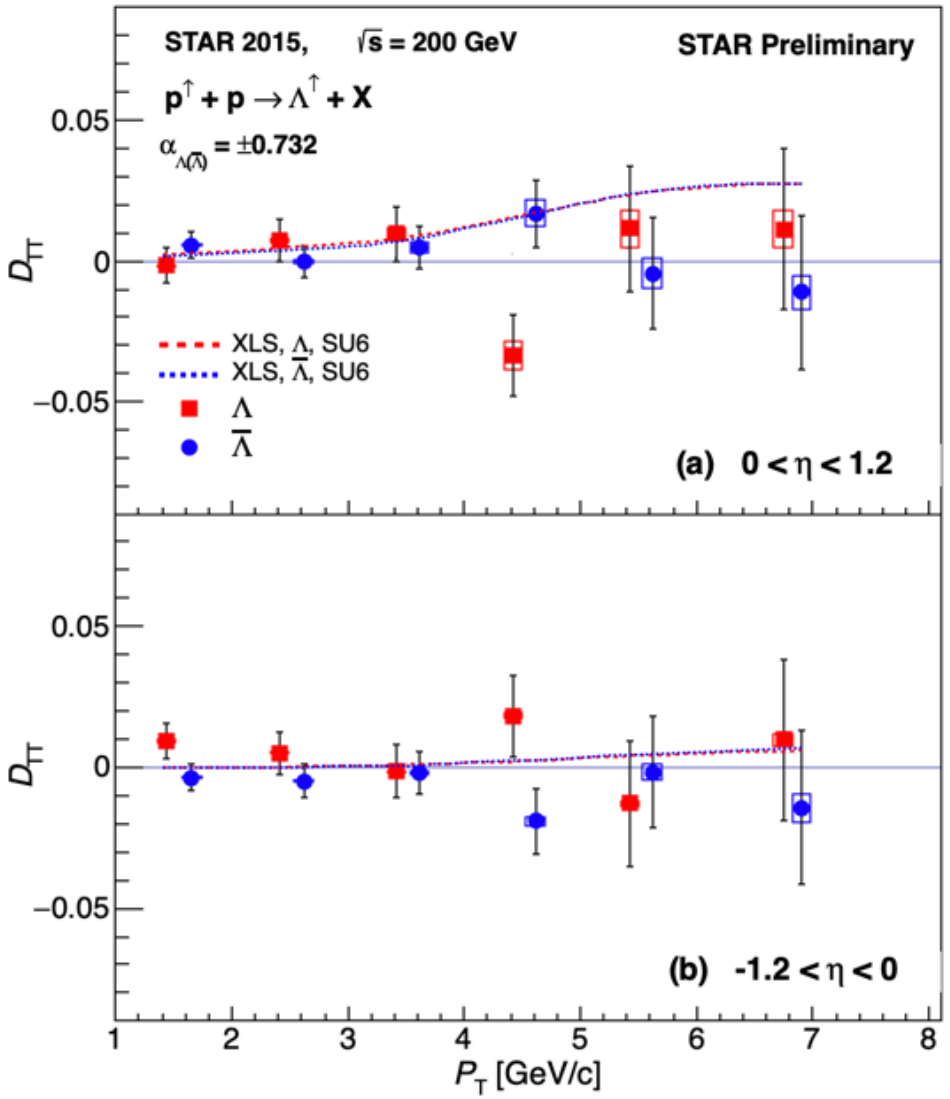
✓ This method was first used in previous STAR measurement, STAR, PRD 98, 091103R (2018)

- $K_S^0$ was also measured to do the null check. The "spin asymmetry" ($\alpha$ of $K_S^0$ is assumed equal to 1) is also consistent with 0 as expected.

STAR, PRD 98, 091103R (2018)



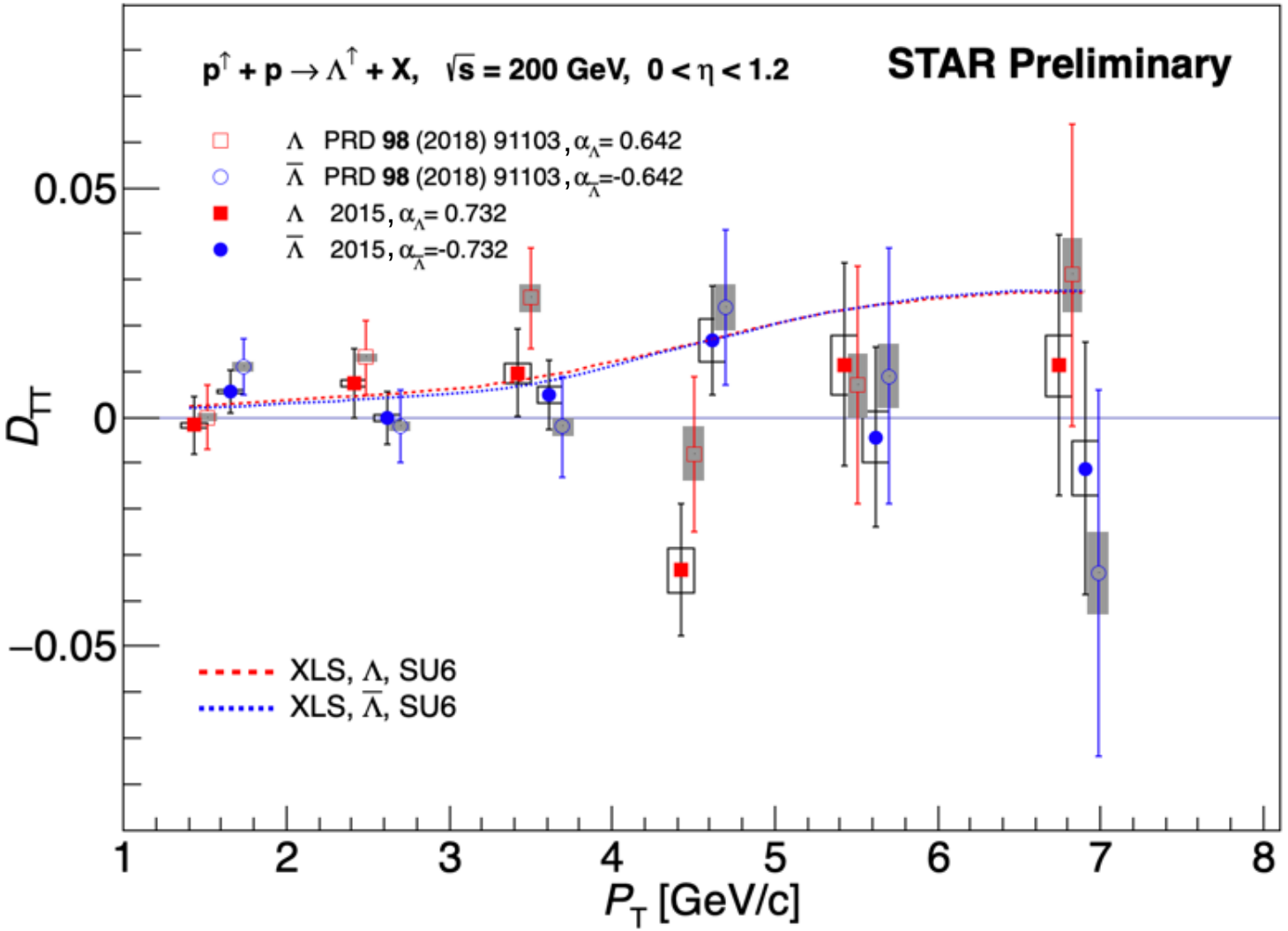
# New $D_{TT}$ results from STAR 2015 data




- New $D_{TT}$ results versus $p_T$ for $\Lambda$ and $\bar{\Lambda}$ in pp collisions at 200 GeV.
- The spin transfer $D_{TT}$ is consistent with the model prediction.
- An indication that strange quark transversity distribution and/or the polarized fragmentation function is small.

Note: The $\Lambda$ results have been offset to slightly smaller $p_T$ values for clarity.

# $D_{TT}$ results comparison from STAR 2015 data and 2012 data




Note: The previously published results have been offset to slightly larger $p_T$ values.

- The 2015 and 2012 $D_{TT}$ results are consistent.
- The new measurements have a factor of $\sim\sqrt{2}$ improvement in statistical precision.

# Summary


- $D_{LL}$ and $D_{TT}$ measurements in pp collisions can provide access to polarized fragmentation function and the strange quark helicity & transversity distributions in the proton.
- New preliminary results of longitudinal spin transfer $D_{LL}$ and transverse spin transfer $D_{TT}$ in pp collisions from STAR 2015 data, with twice the statistics of the previous 2009 data and 2012 data, respectively.
- New preliminary results are consistent with previous measurements, and are still consistent with zero within uncertainties, which may indicate that the strange quark polarized distribution and/or the polarized fragmentation function of $\Lambda(\overline{\Lambda})$ is small.
- STAR forward detector upgrade enables rich $\Lambda$ physics in the forward rapidity region. More p+p data will be collected at STAR in 2022 and 2024.

**Thanks!**